Gravitation and thermodynamic irreversibility for primary matter and antimatter

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Abstract

The irreversibility of macroscopic processes in the universe since its material outset is inferred to stem from such a generalization of the first law of thermodynamics as also covers gravitation. Growth of the total entropy in a comoving Friedmann volume is launched when such a global equilibrium is perturbed with effects of attractive gravitation. It is then underlain by two opposite time arrows definable with the respective gravitational energies of material phases equally created in such a volume from vacuum decay. Due to thermodynamic equilibrium of this process, either of these phases arises homogeneously throughout its entire Friedmann universe. Having first randomly dominated their opposite time arrows, such matter and antimatter thereby polarize the disintegrating vacuum phase with their independent effects of attractive gravitation and hence separate these created phases in terms of their time arrows. For two gravitationally independent material phases created cosmically, their macroscopic inverse of time is equivalent to the identical change of their creation entropies with the respective times. Driven by repulsion of the decaying vacuum phase, cosmic expansion thus largely begets mutually inaccessible matter and antimatter. Dilated at their enhanced densities, either such a progressing time alone still underlies a nongravitational manifestation of the respective entropy growth as well.

1 Introduction

Any of the original formulations by S. Carnot, W. Thomson (Lord Kelvin), M. Planck, and R. Clausius of what is now viewed as the second law of thermodynamics was in terms of impossibility of a certain process for energy transfer without involvement of an external energy [1, 2]. All of them have still been equivalently summarized then as a postulate of irreversibility for macroscopic phenomena [1, 2, 3, 4, 5, 6]. When the statistical foundations of thermodynamics were also put forward by L. Boltzmann [3, 4, 5, 6], however, this postulate was thereby exposed to have a dissonance with the reversibility of laws for microscopic motion. Such apparent inconsistency has thus become the subject of a long-standing debate [3, 6, 7]. It has likewise been recognized in this debate that resolution of the implied paradox would have to stem from an appropriate understanding of the very provenance of material universe [3, 6, 7, 8, 9, 10, 11].

Up until recently, the initial stage of universe evolution had still remained largely obscured, for physically meaningful insights into its nature were staved off by a putatively inevitable singularity at the origin. Consistently with the general hypothesis in [12, 13, 14], however, a univocal cosmological scenario formally avoiding this singularity was eventually revealed [15]. Also in agreement with the hypothesized nature of thermodynamic irreversibility in [3, 6, 7, 8, 9, 10, 11], such a resolution of the problem of cosmological singularity then permitted a nonsingular interpretation for the theory of general relativity as a whole [16]. Having a purely

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macroscopic nature, this theory is thus construed as covariant energy-momentum conservation in such a macroscopically continuous material system as the universe [17, 18, 19, 20, 21, 22, 23].

For the universe properly described by general relativity, the existence of a decaying vacuum phase is formally established [15]. This phase exerts its repulsive effects on a material phase created in the decay process. These effects could then also eventually dominate the global effects of attractive gravitation. The cosmic scenario inferable from [15] thus naturally accommodates an earlier transition to the current stage of accelerated expansion discovered observationally [24]. Rigorously describing the origin of cosmological evolution, this scenario has to provide the only adequate framework for understanding the nature of other observations as well [25, 26, 27]. The initial universe described in [15] still implies an equal emergence of two opposite time arrows [8, 9]. As discussed in [15, 16], it thereby also suggests the formation of two branches of the overall universe either of which would be dominated by one of these arrows and might likewise eventually consist prevalently of matter or antimatter alone [9, 28, 29].

Unlike the reversibility of microscopic physics, however, the two cosmological arrows of time are thus permitted by such a macroscopic theory as general relativity. If construed in terms of the existence of certain microscopic foundations underlying this theory, such time arrows could then be conceptually inconsistent with the purely macroscopic view of general relativity in [16]. As a macroscopic theory that suits either of the opposite cosmological arrows of time in the universe as a whole [8, 9], on the other hand, general relativity might also suggest that gravitation is merely more fundamental than the irreversibility phenomenon. The evolving universe and its time arrows are thus discussed hereinafter from the perspective of specific implications of the formalism in [15] and nonsingular interpretation of general relativity in [16] for the nature of thermodynamic irreversibility and the observed asymmetry between matter and antimatter.

2 Equilibrium thermodynamics in the universe

Let us consider the Friedmann equations [30, 31, 32] in the units with the speed of light $c = 1$:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p), \tag{1}$$

$$(\frac{\dot{a}}{a})^2 = \frac{8\pi G\rho}{3}. \tag{2}$$

Here a is the scale factor, G is the gravitation constant, ρ and p stand for the total energy density and pressure, respectively, the dots denote the derivatives with respect to time, t [33], and the integration constant representing the universe spatial curvature is set to be zero. Only such its value mathematically permits elimination of the initial singularity at $a = 0$ [15]. The cosmological constant is also absent in Eqs. (1) and (2). This is due to its space-time part canceling the material contribution of a constant vacuum energy density for the macroscopically empty space-time [15], to which a reference frame is not definable [16]. Any material phase available in the universe at $a > 0$ is thus rigorously required by Eqs. (1) and (2) to undergo a phase transition to comply with the equation of state for its vacuum phase [12, 13, 14, 15]:

$$p_{|a\to 0} = -\rho_{|a\to 0}. \tag{3}$$

For a quasi static process with ρ and p as are just defined, the first law of thermodynamics is [1, 2]:

$$TdS = T(\frac{ds}{dT}VdT + sdV) = \frac{d\rho}{dT}VdT + (\rho + p)dV, \tag{4}$$

where S is the entropy, V is the volume, $s \equiv S/V$ is the entropy density, and T is the absolute temperature [34]. Eq. (4) implies

$$s = \frac{\rho + p}{T}, \tag{5}$$

and

$$\frac{dp}{dT} = \frac{\rho + p}{T}. \tag{6}$$

Since the universe is a macroscopically continuous material system [16, 33], it has to comply with Eqs. (4), (5), and (6) [35, 36]. When s, ρ, p, and T in the state of a global cosmological equilibrium described by Eqs. (1) and (2) are viewed as the functions of a alone, in particular, Eq. (6) could also be written as

$$\frac{dp}{da} = \frac{\rho + p}{T}\frac{dT}{da}. \tag{7}$$

Relevant when its local effects of attractive gravitation are ignored, such a global equilibrium is realizable in the initial universe, where the vacuum phase is dominant. The proper horizon distance then profusely exceeds a [37, 38]. As discussed in Sec. 3.2 below, this is generally attributable to that $\rho(a)_{|a \geq 0} < \infty$.

For an adiabatically isolated spatial volume with a as its linear dimension, Eq. (4),

$$d(\rho a^3) + pd(a^3) = 0,$$

could also be rewritten as

$$\frac{d\rho(a)}{da} = -3\frac{\rho(a) + p(a)}{a}. \tag{8}$$

When multiplied by $\dot{a}$ and a is treated as the scale factor, Eq. (8) is also formally derivable both from Eqs. (1) and (2) and from covariant divergence of the material energy-momentum tensor for a perfect fluid in the Einstein field equations with the Friedmann-Robertson-Walker (FRW) metric. Consistently with what one could expect from the universe as a whole [33], a comoving Friedmann volume is thus viewable as adiabatically isolated. As seen from Eq. (8) then, decay of the vacuum phase begins when a grows from 0, $\rho(a)$ decreases from its maximum at $a \to 0$, and $p(a)$ increases from its respective minimum defined by Eq. (3) [15].

Eq. (7) thus suggests that $dT/da > 0$ when $dp/da > 0$ and $p > -\rho$. Extrapolating the material vicinity of $a = 0$, therefore, $T = 0$ is expected in the purely vacuum state described by Eq. (3). A very high temperature characterizing what is commonly viewed as Big Bang is thus separated from small T and a at which a material phase first arises by a finite time interval when the material universe is largely dominated by its vacuum phase [39]. During this interval, the temperature of the emerging material phase has to grow with the density of such a phase. A massive vacuum-phase disintegration into the material phase, the Big Bang, is then triggered by the onset of nonlinearity in the Friedmann equations at a large enough a [15]. A major part of the overall material phase for the present universe thus becomes available when the total density of such a phase begins to decrease. The temperature then also has to turn decreasing to eventually reach the current temperature of Cosmic Background Radiation (CBR).

When all thermodynamic parameters, s, ρ, p, and T, of a material volume are entirely specified by a, such a volume has to be undergoing a quasi static process: it remains in the state of a thermodynamic equilibrium at any a. For the comoving volume, this means that a deviation from such an equilibrium of a material phase within this volume is ignored. [As mentioned above and discussed in Sec. 3.1, this deviation is underlain by certain effects of attractive gravitation that are not allowed for by Eqs. (1), (2), and (8) alone.] Such a quasi static process as is also adiabatically isolated, according to Eq. (8), would however have to have a constant entropy [1, 2, 40]. When $S \equiv (a^3 s)$ is differentiated with respect to a and Eqs. (5), (7), and (8) are used, in particular, one obtains

$$\frac{dS}{da} = \frac{d(a^3 s)}{da} = 0 \tag{9}$$

for any $a \geq 0$.

As seen from Eq. (9), $s(a)$ is proportional to a^{-3} [40]. To avoid infinite $s(a)_{|a\to 0}$, however, the constant of proportionality would have to be zero. This constant is still what stands for the entropy of (a comoving volume for) such a homogeneous (Friedmann) universe. Consistently with the Nernst theorem [1, 2], therefore, $S(a) \to 0$ when $a \to 0$ and $T(a) \to 0$. The initial state of the universe then has the lowest possible entropy [3, 6, 7, 8, 9, 10, 11].

When the constant $S(a)$ is defined by the initial vacuum state at $a = 0$ exactly, however, Eq. (5) for $s(a) = s(0) = 0$ suggests that decay of the vacuum phase is not permitted. This also follows from

$$\frac{ds}{da} = \frac{1}{T}\frac{d\rho}{da}, \tag{10}$$

which is likewise implied by Eq. (4) [41]. As seen from Eqs. (8) and (10), $ds/da < 0$ for $a > 0$ only when a material phase is present, i.e. $p > -\rho$, if such a phase arises as an initial fluctuation with $S > 0$. So long as $ds/da = 0$ in Eq. (10), however, $d\rho/da = 0$ and $p = -\rho$ in Eq. (8). A value of $a > 0$ could then also be viewed as having no real physically meaningful definition either. Such a definition arises only with at least a small density of the material phase.

Since $\rho(-a) = \rho(a)$ and $p(-a) = p(a)$ in Eqs. (1) and (2), $[d^{(2n+1)}\rho(a)/da^{(2n+1)}]_{|a=0} = [d^{(2n+1)}p(a)/da^{(2n+1)}]_{|a=0} = 0$ $(n = 0, 1, 2, ...)$ [15]. Given also that $T(a)_{|a=0} = 0$, one could thus apply the l'Hospital rule to Eqs. (5) [for $s_{|a\to 0} \to 0$] and (10) [for $|(ds/da)_{|a\to 0}| < \infty$]. Denoting then the order of the first nonzero derivative of $T(a)$ at $a = 0$ as n_T, this leads to

$$[\frac{d^{(n)}\rho(a)}{da^{(n)}}]_{|a=0} = -[\frac{d^{(n)}p(a)}{da^{(n)}}]_{|a=0} = 0, \quad n = 1, 2, ..., n_T. \tag{11}$$

Eqs. (5), (10), and (11) then imply that a material phase could arise near $a = 0$ only at the order of at least either $a^{(n_T+1)}$ for $n_T = 2n + 1$ or $a^{(n_T+2)}$ for $n_T = 2n$ when $n = 0, 1, 2, ...$

Emergence of the material phase as a fluctuation is discussed in Sec. 3.2 below. Once such a phase has macroscopically formed out of its vacuum state, however, it physically defines the real scale factor $a > 0$. Irrespective of its nature, variation of $a > 0$ thus controls the mutual transition between the vacuum and material phases. So long as all thermodynamic parameters are specified by a alone, in addition, proportionality of the entropy density to a^{-3} is still suggested by Eq. (9). The constant of proportionality is then defined by the positive entropy of the overall material phase produced by the initial fluctuation. (Arising at a finitely small $a > 0$ [39], this constant entropy is not zero.) Along with the temperature, such a change of the entropy density with a also specifies that of the energy density in Eq. (10).

3 Onset and evolution of two opposite time arrows

3.1 The concept of time

Given Eq. (9), thermodynamic irreversibility could not thus arise in the universe maintaining the states of global material equilibrium. Although these equilibrium states are formally implied by Eqs. (1) and (2), however, the universe expansion could be meaningfully described in the framework of these equations only when their such a parameter as time has a physical manifestation. A covariant formulation of energy-momentum conservation thus results. It is such a covariant conservation law that identifies the phenomenon of gravitation [16]. With its repulsive manifestation, this phenomenon is then what drives the cosmological expansion.

Even when described by the Friedmann equations, however, such a cosmic expansion itself is still irrelevant to the nature of thermodynamic irreversibility. On the other hand, the time variable emerges in Eqs. (1) and (2) along with two other functions of a, $\rho(a)$ and $p(a)$. Having to agree with the cosmological role of this variable, the thermodynamic nature of time thus has to arise from physical processes other than those described by the Friedmann expansion [42, 43].

Indeed, a real comoving volume does not maintain its initial Friedmann background equilibria. Once a material phase has formed macroscopically, its attractive gravitation gives rise to dissipative processes [44] and, eventually, to gravitational instability of its Friedmann equilibria as well [45]. (Such a gravitationally unstable comoving volume would then evolve towards a complex equilibrium system consisting of multiple subsystems so that only each of them alone have a local equilibrium [46].) Any of the putative global equilibria thus sought has to be thermodynamically disparate from its background Friedmann equilibria treated in Sec. 2.

What is known about thermodynamic irreversibility stems from the gravitational instability for a material phase of vacuum decay in our comoving volume. It is also subject to local effects of attractive gravitation. Introducing the global effects of dissipation as well [44], attractive gravitation is thus viewable as a primary manifestation of the thermodynamic time arrow in the universe [10, 47, 48]. Driven by repulsive gravitation, as described by Eqs. (1) and (2) and their time variable, the cosmological expansion is also meaningful only when a material phase has formed. Creation of such a phase thus underlies both foundational manifestations for the time arrow driven by gravitation.

Although general relativity is described with the time variable, this theory likewise specifies how time changes with respect to material energy sources. When time and space intervals are materially defined [16], in addition, they are inherently related even in the theory of special relativity. The only comprehensible way to physically link such seemingly independent concepts as time and space in the framework of the relativity theory is thus to have time defined in terms of a phenomenon described by the most general form of this theory. Gravitation within general relativity might then also be what introduces the time arrow in terms of relevant properties of the emerging material phase, as suggested just below and discussed in Secs. 3.2 and 3.3.

During the cosmological expansion, gravitational attraction of a material phase created in its comoving volume by vacuum decay could thus stand for the thermodynamic time arrow. With the microscopic CPT symmetry [49] of the vacuum phase, however, the decay process implies the formation of two opposite time arrows. It also has to equally create such material phases as matter and antimatter throughout the universe. The observationally accessible space is still overwhelmingly filled with matter alone [28]. In the spatially infinite universe, this is possible only if matter and antimatter are separated by their such an irreversible CPT coordinate with opposite arrows as time [50]. Both signs for time then also agree with Eqs. (1) and (2).

Given creation and annihilation operators in flat space-time, $\hat{\psi}^\dagger$ and $\hat{\psi}$, respectively, the introduction of antimatter with the same time arrow as for matter (as say in §11 of Ref. [49]) is also interpretable in terms of two opposite time arrows that have to equally arise from decay of the vacuum phase. Creation (annihilation) of say a scalar particle with one arrow of time could thus be linked to such a creation (annihilation) of its antiparticle with the opposite time arrow. With 3-momentum $\mathbf{p}$, energy ε, and 3-vector $\mathbf{x}$ for the spatial coordinates of the particle, when superscripts $^{(+)}$ and $^{(-)}$ refer to the modes with ε and $-\varepsilon$, respectively, this is seen from:

$$\hat{\psi}^\dagger(t,\mathbf{x}) = \sum_{\mathbf{p}} \frac{1}{\sqrt{2\varepsilon}} \hat{a}^{\dagger(+)}_{\mathbf{p}} e^{-i(\mathbf{px}-\varepsilon t)} + \sum_{\mathbf{p}} \frac{1}{\sqrt{2\varepsilon}} \hat{a}^{\dagger(-)}_{\mathbf{p}} e^{-i[-\mathbf{p}(-\mathbf{x})-\varepsilon(-t)]} =$$

$$\sum_{\mathbf{p}} \frac{1}{\sqrt{2\varepsilon}} \hat{a}^{\dagger(+)}_{\mathbf{p}} e^{-i(\mathbf{px}-\varepsilon t)} + \sum_{\mathbf{p}} \frac{1}{\sqrt{2\varepsilon}} \hat{b}^{\dagger(+)}_{\mathbf{p}} e^{-i[\mathbf{p}(-\mathbf{x})-\varepsilon(-t)]}, \tag{12}$$

$$\hat{\psi}(t,\mathbf{x}) = \sum_{\mathbf{p}} \frac{1}{\sqrt{2\varepsilon}} \hat{a}^{(+)}_{\mathbf{p}} e^{i(\mathbf{px}-\varepsilon t)} + \sum_{\mathbf{p}} \frac{1}{\sqrt{2\varepsilon}} \hat{a}^{(-)}_{\mathbf{p}} e^{i[-\mathbf{p}(-\mathbf{x})-\varepsilon(-t)]} =$$

$$\sum_{\mathbf{p}} \frac{1}{\sqrt{2\varepsilon}} \hat{a}^{(+)}_{\mathbf{p}} e^{i(\mathbf{px}-\varepsilon t)} + \sum_{\mathbf{p}} \frac{1}{\sqrt{2\varepsilon}} \hat{b}^{(+)}_{\mathbf{p}} e^{i[\mathbf{p}(-\mathbf{x})-\varepsilon(-t)]}, \tag{13}$$

where $\hat{a}^{\dagger(\pm)}_{\mathbf{p}}$ and $\hat{b}^{\dagger(\pm)}_{\mathbf{p}} \equiv \hat{a}^{\dagger(\mp)}_{-\mathbf{p}}$ as $\hat{a}^{(\pm)}_{\mathbf{p}}$ and $\hat{b}^{(\pm)}_{\mathbf{p}} \equiv \hat{a}^{(\mp)}_{-\mathbf{p}}$ are related by the C transformation.

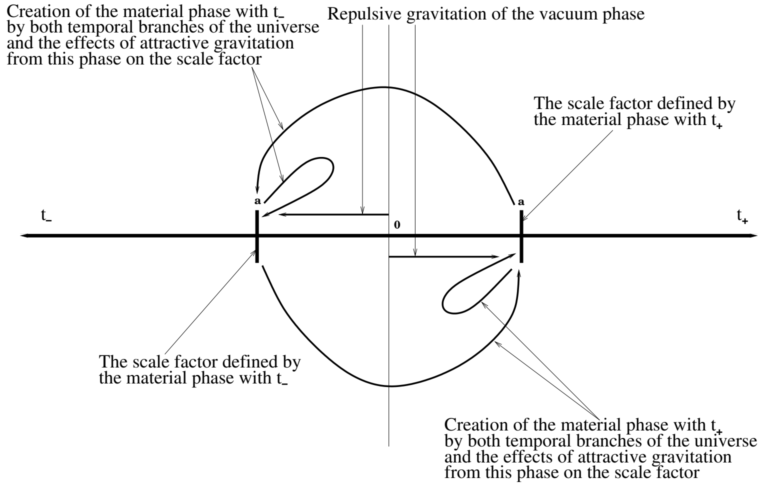

Figure 1: Schematic diagram for creation and expansion of two material phases with $t_\pm$ and for the independent effects of attractive gravitation from these phases on the scale factor.

If formed per Eq. (12), the opposite cosmological arrows of time would have to match the common quantum characteristics of the respectively created overall material phases. However, either of these time arrows then also has to agree with the above entropy production due to attractive gravitation. Such a gravitation thus ought to apply independently to either overall material phase defined by its emergence from the vacuum phase with the same PT signature [51, 52] and so to warrant the space-time flatness for Eq. (12) [53]. As discussed in Sec. 3.3 below, physically distinct matter and antimatter are then created largely with the same opposite time arrows. Such matter and antimatter are thus separated in terms of their time coordinates.

As a thermodynamic time measure for either of the material phases arising from vacuum decay, the entropy growth above the initial Friedmann entropy is launched (with dissipative processes [44] and gravitational instability [45]) as soon as these material phases emerge. Underlain by attractive gravitation, however, the perturbations giving rise to such a growth are ultimately driven independently by either of two total (active) gravitational energies with opposite time arrows created in its comoving volume. Since the nature of energy responsible for a local time dilation is likewise gravitational, these total energies could thus represent the thermodynamic arrows of such times as arise in Eq. (12). Also gauging any stage of cosmic evolution, the gravitational energies so created then stand for the respective cosmological time arrows as well [54].

When either overall material phase created with the same time arrow [55] in the background Friedmann universe is viewed as a perfect fluid, the respective measures of opposite time arrows for such cosmological phases, $t_+(a)$ and $t_-(a)$, are thus definable as (Fig. 1):

$$t_\pm(a) \equiv \alpha_\pm \int_{a_i}^{a} dx_3 \int_{a_i}^{a} dx_2 \int_{a_i}^{a} [\rho_\pm(x_1, x_2, x_3) + 3p_\pm(x_1, x_2, x_3)] dx_1, \tag{14}$$

where $a_i > 0$ is the scale factor at which both material phases initially emerge [56], ρ_+ and p_+ are the total energy density and pressure, respectively, of one overall material phase created with the same time arrow from decay of the cosmic vacuum phase, ρ_- and p_- are these parameters for such a phase with the opposite time arrow, whereas α_+ and α_- are coefficients also accounting for the dimensionality. [In Eqs. (1) and (2), ρ and p thus include the homogeneous version either of ρ_+ and p_+ or of ρ_- and p_-, respectively [57].] Since the two created material phases comply with the CPT symmetry, however, $\alpha_- = -\alpha_+$ is thereby implied. Identified in terms of Eqs. (14) during vacuum decay, therefore, the time absolute magnitude could only increase with the scale factor. It has to do so even when a local process whose entropy increases or looks unchanged seems to be unaffected by gravitation [58]. The time dilation at a comparatively dense source of gravitational energy (say admitting such a process) is then attributable to the relative reduction of the growing gravitational effect for the respective global time scale in Eqs. (14) on this source.

3.2 Emergence of the time arrows

At $a = 0$ exactly, the absence of a material phase still prevents time from having its physical manifestation suggested in Sec. 3.1. The notion of thermodynamic irreversibility also applies only to such a material phase as could beget the equilibrium states with growing entropy by itself. Driven solely by its own attractive gravitation, however, either of the two overall material phases arising with opposite time arrows from their vacuum phase [55] does have such states independently of the other. Both time and thermodynamic irreversibility then acquire their physical meanings only once a small $a = a_i > 0$ itself has been endowed such a real meaning when the density of either material phase turns at least slightly larger than zero.

Arising from an appropriate CPT-invariant macroscopic fluctuation, either overall irreversible material phase would thus break the time-reversal symmetry of the initial vacuum state by its one of the two opposite time arrows. In terms of quantum mechanics, this fluctuation still ought to be consistent with both time-energy uncertainty relations. Admittedly, however, such a relation applies to microscopic physical phenomena when time is available as an external macroscopic parameter. In particular, its general validity has thus also been disputed [59].

To the times defined by Eqs. (14), their respective uncertainty relations still do apply. As say the momentum or position of a microscopic particle, either time is then in fact an intrinsic characteristic of such a quantum system as the universe branch defining it [60]. The respective quantum fluctuations begetting such times also prove to be physically consistent with Eqs. (1) and (2), whose underlying assumptions introduce the comoving-volume concept for Eqs. (14). Given Eq. (2), indeed, the proper horizon distance at $a = a_i$, $d_p(a_i)$, is found to be infinite:

$$\frac{d_p(a_i)}{a_i} = \int_0^{a_i} \frac{da}{\dot{a}a} = \lim_{a_0 \to 0} \int_{a_0}^{a_i} (\frac{a}{\dot{a}}) \frac{da}{a^2} = \lim_{a_0 \to 0} [(\frac{3}{8\pi G \rho[\bar{a}(a_0)]})^{\frac{1}{2}} \int_{a_0}^{a_i} \frac{da}{a^2}] \to \infty, \quad \bar{a} \in (a_0, a_i), \quad (15)$$

for $\rho(a)_{|a \geq 0} < \infty$ [61, 62]. Vacuum decay thus commences in the state of thermodynamic equilibrium for the entire universe [38]. Also due to its CPT invariance, therefore, both virtual material phases have to arise homogeneously as the uncertainty intervals of their respective times, viewable per Eqs. (14) with $a_i = 0$ [62, 63]. The virtual existence of an appropriate energy portion for either of these material phases then also yields its time-energy uncertainty [60].

First identified by its uncertainty interval itself, either time for such an interval is thus introduced by the virtual gravitational energy of its overall material phase. Space-time curvature is however also defined then by the material energy-momentum [16]. Either virtual material phase thus undergoes its own attractive gravitation, which acts independently of the other phase. Given their irreversibility, attributable to such gravitational effects, the two opposite virtual time arrows thus prohibit annihilation of the material phases underlying them. This launches the real time arrows by creating their respective material phases at $a = a_i$. These arrows are then enhanced by a further vacuum decay with the same spatial expansion of both overall material phases [50]. Also driven by repulsive gravitation of the decaying vacuum phase, such processes conform with the total thermodynamic energy balance for this phase [15, 16].

The time arrows introduced by Eqs. (14) are thus continuously extended. Since the CPT symmetry implies their opposite signs [as in Eq. (12)], the material phases arising from the decaying vacuum phase also undergo their effects of attractive gravitation independently. As in their virtual state, these real material phases are then macroscopically separated in terms of such time arrows (Fig. 1) [55]. Despite this separation, the equal absolute magnitudes of times in Eqs. (14) are still identified by the same scale factor. Its growth is driven by the respective effects of repulsive gravitation identically exerted by the decaying vacuum phase on either created material phase. The CPT symmetry thus describes both the decay process and all the underlying gravitational effects. The combination of such a spatially synchronous creation of the entangled material phases with their mutual inaccessibility is also touched on in the end of Sec. 4.

3.3 Separation between primary matter and antimatter

Since the inertial density (which could also be referred to as the passive gravitational density) of the vacuum phase $\rho + p = 0$, this residual phase preserves its homogeneity in the presence of material phases as well. At any stage of its decay, therefore, the vacuum phase could be treated as the initial state of an abstract Friedmann universe with the same vacuum density [15]. New created material phases are then viewable as such very first ones. They would consequently have a new scale factor growing from zero and the infinite proper horizon distance, as suggested by Eq. (15) for such a scale factor. The vacuum-decay process throughout the universe evolution thus ought to possess the same kind of thermodynamic equilibrium as for the initial vacuum phase discussed in Sec. 3.2.

The CPT symmetry likewise has to apply to decay of the vacuum phase during the entire cosmic evolution. When the two material phases homogeneously created in this decay process are physically identical, their opposite PT signatures for the respective creation operators [as in Eq. (12)] comprise the only distinction between them [64, 65, 66]. Defining either time arrow in these signatures, the independent effects of attractive gravitation are enhanced by vacuum decay into such material phases. These phases are then also found to be mutually inaccessible, although their spatial location and physical properties are identical [50].

A specific association of either arrow of time with matter or antimatter turns meaningful only when a distinction between these phases other than that due to their PT signatures has emerged as well. This association is then first randomly determined by a small dominance of either such a signature within one of these material phases. Once this initial dominance has been established, however, it gives rise to polarization of the vacuum phase by the PT signatures prevalent in the existing physically distinguishable matter and antimatter.

Such a vacuum polarization ought to underlie the evolution of both real time arrows when physically distinct components of matter and antimatter are created directly from vacuum decay. In particular, the particle-antiparticle pairs arising from an unpolarized vacuum phase would have randomly opposite PT signatures. This would have lead to no net creation of either physically distinguishable phase, due to annihilation of the particles and antiparticles with the same time arrow. Only radiation with either time arrow would have then resulted.

The vacuum-phase polarization is due to the effects of attractive gravitation on both physically distinct virtual phases. Any two entangled (virtual) particles of these phases must have opposite time arrows that match their independent effects of attractive gravitation. Once either of such real phases has randomly dominated its one of the two time arrows, however, it also ought to respectively attract only the same (rather than the contrary) virtual phase. Attractive gravitation thus predominantly imposes such opposite PT signatures on the virtual particles of physically distinguishable matter and antimatter as are gravitationally identified by the respective already existing phases. Either of these real phases is then also created out of its vacuum-phase progenitor to prevalently have the same time arrow. A small initial dominance of physically distinct material phases within their respective PT signatures is therefore enhanced throughout such a decay process. It then also results in the observed macroscopic separation between the created matter and antimatter in terms of their time arrows.

With the independent respective identifications of both time arrows by attractive gravitation, the opposite PT signatures of two material phases arising from their parent vacuum phase thus behave as entangled quantum properties suggested say by Eq. (12). Along with the charge distinction, if any, such properties gravitationally distinguish between these phases when the latter symmetrically emerge from their vacuum-phase progenitors. Due to their polarizing effects of attractive gravitation on the vacuum phase, the created matter and antimatter thus have largely the same respective PT signatures. These material phases are then also rendered mutually inaccessible in terms of their opposite time arrows [50].

Given their CPT symmetry, however, the residual vacuum phase and its repulsive gravitation have no preference in the formation of time arrows. They permit virtual matter and antimatter with either combination of PT signatures and so equal creation of such respective real phases. Since decay of the vacuum phase is actually driven by the repulsive gravitation exerted by this phase as well, a relatively smaller portion of antimatter (matter) could thus still arise with the time arrow for which the dominance of matter (antimatter) has been established by the vacuum polarization with attractive gravitation [67]. Such a minor material phase is therefore eventually eliminated by its annihilation with the dominant one. The resulting radiation then has the time arrow shared by its matter and antimatter progenitors.

Under appropriate conditions, radiation of either time arrow could also give rise to a pair of physically distinct particle and antiparticle. Both of these then have the original radiation time arrow. Nonrelativistic antiparticles could thus eventually exist in our temporal branch of the universe for this reason as well, before they are annihilated with their matter counterparts. Another source for the observable antimatter is decay of massive particles. P and CP violations then in weak interactions [68, 69, 70] and a purely leptonic CP violation [71] are thus attributable to microscopic manifestations of the same original PT signature for the involved particles and antiparticles [67]. With the arrow of time opposite to ours, however, the antimatter created directly from decay of the vacuum phase has to be fundamentally inaccessible.

4 Thermodynamic irreversibility

Ignoring the CPT symmetry macroscopically [say $\alpha_- \neq -\alpha_+$ in Eqs. (14)], let $t_+(a)$ and $t_-(a) \neq t_+(a)$ be still defined by Eqs. (14) according to the microscopic PT signatures of the created material phases. In terms of the gravitational time arrow, $t_\pm(a)$ thus likewise underlies deviation from the initial Friedmann entropy caused by such an attractive gravitation as applies to its respective material phase independently of the other (Sec. 3.1). These material phases arise from such a universally relevant process as vacuum decay (Fig. 1). To any scale factor then, there corresponds a new thermodynamic equilibrium for either material phase that results from the perturbative effects of attractive gravitation within this phase [72]. Both these equilibria could actually form ultimately only after an additional expansion of the comoving volume (and creation of the material phases) whose effects on them are ignored. They are therefore treated below as quasi equilibria. Either of these putative global equilibria would thus have an entropy viewable to correspond to the above scale factor and its instant of the respective time.

According to our experience summarized as the second law of thermodynamics, the entropy just defined has to exceed that of the background Friedmann equilibria initially specified by a_i alone [10, 47, 48, 72]. Let this entropy for the material phase with $t_\pm$ be respectively equal to $S+\tilde{S}_\pm$, where $\tilde{S}_\pm > 0$. The overall entropy rise in both (spatially identical) comoving volumes is then $\tilde{S} \equiv \tilde{S}_+ + \tilde{S}_-$. The nature of deviation for the quasi equilibrium state with entropy $S+\tilde{S}_\pm$ from its background equilibrium with initial entropy S is thus due to attractive gravitation. This implies that $\tilde{S}_\pm$ would be the larger the more of its material phase there is integrally within the comoving volume. So long as creation of the material phases continues, therefore, $\tilde{S}_\pm$ could only increase. However, the overall universe with both created material phases still has to be viewed as an adiabatically isolated system even in its putative states of quasi equilibria. $2S+\tilde{S}$ thus has to be independent of a, although this could not be illustrated directly like Eq. (9) is derived for S. $\tilde{S}_\pm$ would then have to be respectively identified by $t_\pm$ alone.

Irrespective of the CPT symmetry in Eqs. (14), therefore, the condition that the overall putative state of quasi equilibria for both material phases be adiabatically isolated is:

$$\frac{d[2S + \tilde{S}(t_+, t_-)]}{da} = 0. \tag{16}$$

Allowing for Eq. (9), Eq. (16) is also rewritten as

$$\frac{\partial \tilde{S}(t_+, t_-)}{\partial t_+}\frac{dt_+}{da} + \frac{\partial \tilde{S}(t_+, t_-)}{\partial t_-}\frac{dt_-}{da} = 0. \tag{17}$$

Both $\tilde{S}_+(t_+)$ and $\tilde{S}_-(t_-)$ result from general relativity for a spatially identical comoving volume. $\tilde{S}_+$ is thus the same function of t_+ as $\tilde{S}_-$ is of t_-. Since $t_-(a) \neq t_+(a)$, however, let us assume that $\tilde{S}$ varies equally with its times when the material phases are created at a given a [73]:

$$\frac{\partial \tilde{S}(t_+, t_-)}{\partial t_+} = \frac{\partial \tilde{S}(t_+, t_-)}{\partial t_-}[\Longrightarrow \frac{\partial^{(n)} \tilde{S}(t_+, t_-)}{\partial t_+^{(n)}} = \frac{\partial^{(n)} \tilde{S}(t_+, t_-)}{\partial t_-^{(n)}}, \quad n = 2, 3, ...]. \tag{18}$$

In addition, creation of the material phases renders the entropies of their gravitationally produced (independent) putative quasi equilibria only growing with the respective times:

$$\frac{d\tilde{S}_+(t_+)}{dt_+} = \frac{\partial[\tilde{S}_+(t_+) + \tilde{S}_-(t_-)]}{\partial t_+} = \frac{\partial \tilde{S}(t_+, t_-)}{\partial t_+} = \frac{\partial \tilde{S}(t_+, t_-)}{\partial t_-} = \frac{d\tilde{S}_-(t_-)}{dt_-} > 0. \tag{19}$$

Eqs. (17) and (18) as well as inequality (19) then imply:

$$\frac{d(t_+ + t_-)}{da} = 0. \tag{20}$$

From Eqs. (14), however, $t_+ = t_- = 0$ at $a = a_i$. Eq. (20) thus leads to

$$t_-(a) = -t_+(a) \equiv -t(a), \tag{21}$$

as implied by Eqs. (14) with the CPT symmetry and permitted by Eqs. (1) and (2).

On the other hand, let Eq. (21) be valid. This is implied by Eqs. (14) with the CPT symmetry and permitted for the macroscopic time variables by Eqs. (1) and (2). The adiabaticity of any above overall equilibrium and quasi equilibrium state for both material phases thus likewise leads to the validity of Eqs. (16) and (17). Since $dt/da > 0$ once the material phases have emerged, as say suggested by Eqs. (14), Eq. (17) then implies Eqs. (18) and (19). Generally, therefore, such a formal equivalence between Eqs. (18) and (21) applies to any two material phases being jointly created in the universe whose distinct times are identified per Eqs. (14) by gravitation acting independently for either of these phases.

When the time concept arises from decay of the vacuum phase, separate time arrows are thus defined for two material phases thereby created. The identical thermodynamic role of these arrows at the creation of their material phases is also equivalent to what is implied by the microscopic CPT symmetry [9, 15, 16, 29]. The gravitational nature of both CPT time arrows then links the microscopic and macroscopic physics. In terms of thermodynamic irreversibility, the role of $-t$ for its phase (accumulating say antimatter) is indeed the same as that of t for the contrary phase (accumulating matter) at the same a. The latter thus stands for the absolute magnitude of both times. For either material phase, however, the other is inaccessible in terms of their time coordinates, despite their identical spatial location [50]. These time coordinates are generally connected via the cosmological and thermodynamic past of the respective material phases in their vacuum phase [74]. Such a past is unreachable since gravitation only increases the time absolute magnitude and entropy for either created material phase. Generated by cosmic expansion and decay of the vacuum phase, either of the time arrows arising from Eqs. (14) is thus what underlies the irreversibility for entropy growth in respective local processes of a seemingly nongravitational nature as well [8, 58, 75].

5 Summary and conclusions

In its nonsingular global thermodynamic equilibrium described entirely by the Friedmann equations, the universe consists of the vacuum phase alone and is characterized with $a = 0$. The constant entropy of such an adiabatically isolated system then also has to be zero. The concepts of time, spatial expansion, and entropy growth thus arise only when an $a > 0$ has been introduced by emergence of a material phase throughout the universe. Rendering the equilibrium entropy positive, this phase establishes such mutually representing concepts as time and gravitation. Attractive gravitation of the created material phase then launches dissipative processes in the perturbed Friedmann equilibria and, eventually, renders such equilibria gravitationally unstable. The universe entropy is thus increased above its initial value for the material Friedmann equilibria. Enhancing the material phase in its expanding comoving volume, decay of the vacuum phase (repulsively) driving such an expansion also gives rise to the cosmological arrow of time. This renders the global entropy growth continuous. Described in terms of the time variable, gravitation thus underlies the cosmological and thermodynamic aspects of this variable.

A material phase expected to bring the time notion into the Friedmann formulation also arises throughout the universe consistently with this formulation. Such an emergence of the material phase is underlain by the homogeneity of vacuum decay into it. With the infinite proper horizon distance for this process in the initial vacuum phase, in particular, the disintegration of this phase commences in the state of global thermodynamic equilibrium. Since homogeneity of the vacuum phase is unaffected by a material product of its decay, however, the homogeneous spatially infinite vacuum state of any density formed at subsequent stages of the decay process is also viewable as the initial state of a respective Friedmann universe. Vacuum decay then has to be in thermodynamic equilibrium at any stage of cosmic evolution.

Also invariant to CPT, however, the vacuum phase has to decay into two material phases with opposite PT signatures. Either of the opposite time arrows thus forming cosmologically by the respective material phase then has to likewise agree with the entropy growth arising from the effects of dissipation and clustering driven by attractive gravitation. Such a gravitation is consequently manifested independently for these two material phases even when they are indistinguishable otherwise. Consistently with the relative dilation of time at a locally enhanced source of gravitational energy, the absolute magnitude for either time is thus quantitatively definable with the (active) gravitational energy of the overall material phase arising for the respective time arrow from the vacuum phase in a Friedmann comoving volume.

The cosmic vacuum phase could thus be unstable only to the formation of two homogeneous material phases. Either of these phases would also have to identify its own cosmological time arrow. In particular, such a virtual material phase introduces the uncertainty time interval and gravitation as mutually describing concepts. Since this time interval is a finite (comoving-volume) characteristic of such a quantum system as its overall homogeneous material phase, the time-energy uncertainty underlying the virtual state for any corresponding finite portion of material energy is applicable as well. The virtual material phases are then materialized with the feedback coming from their independent effects of attractive gravitation. As the opposite (thermodynamic) time arrows, these gravitational effects inhibit annihilation of the virtual material phases and thereby create such real phases. The respective real time arrows are thus likewise launched. Driven by repulsion of the residual vacuum phase, expansion of such created material phases then also enhances their time arrows with a further vacuum-phase decay.

When the two material phases emerging from decay of the vacuum phase are physically distinct, their respective macroscopic associations with the opposite PT signatures are first randomly established. Such an association is still maintained then due to gravitational polarization of the vacuum phase. The virtual time arrows for matter and antimatter are largely imposed on this phase by the independent effects of attractive gravitation as these are identified by the initial dominance of the respective real phases in their opposite time arrows. These effects hence result in creation of the physically distinguishable material phases with such PT signatures as characterize their respective already existing phases. Consequently, matter and antimatter consistently arise from decay of their vacuum phase with mainly the same opposite time arrows, although these matter and antimatter are spatially identical. The opposite PT signatures are thus such gravitationally specified quantum characteristics as, along with the charge distinctions, if any, always distinguish between the material phases created from vacuum decay. This is what explains why such matter and antimatter are principally inaccessible to each other.

What is viewed as antimatter in our temporal branch of the universe is accessible only because such an antimatter has the same time arrow as matter. A minor portion of one of these material phases could still arise for the time arrow largely characterizing the other such a phase. One contribution to this portion is permitted by the residual vacuum phase and its repulsive gravitation. Their effects are symmetric to the sign of PT signature for the created material phases. Another source of such an antimatter is decay of relativistic and nonrelativistic particles with our time arrow into matter and antimatter with the same time arrow. P or CP violations in such [68, 69, 70] and other [71] processes are then due to the single PT signature for all the involved particles and antiparticles [67].

The time-reversal invariance in microscopic physics is thus attributable to the CPT symmetry between the created material phases, for which such a physics has to be identical. For any two gravitationally independent material phases created cosmically, their macroscopic opposite of time is equivalent to the identical change of their creation entropies with the respective times. This concordance between the microscopic and macroscopic physical properties is underlain by the macroscopic nature of time, which is entirely attributable to gravitation. The thermodynamic nature of either time arrow stems from attractive gravitation for the respective material phase. Enhancing either such a phase with vacuum decay and repulsive gravitation, the vacuum phase thus also drives both cosmological time arrows. In terms of the microscopic time-reversal symmetry, the irreversibility of such macroscopic processes as ought to be unaffected by attractive gravitation is then due to their single cosmologically available time arrow [8, 58].

The irreversibility of either cosmological time arrow is thus in its turn attributable to augmentation of the gravitational energy for the overall material phase arising with this arrow of time in its comoving volume. Due to the attractive gravitation of such a phase, this volume is driven towards a new putative quasi equilibrium with an ever higher entropy. This transition includes such processes at a locally enhanced gravitational density as their entropy appears to stay constant until affected by the globally sought quasi equilibrium and eventually by the cosmological creation of the respective material phase. Both the attractive gravitation of either created material phase and the repulsive gravitation exerted on such a phase by the decaying vacuum phase are then due to covariant energy-momentum conservation. This conservation law is manifested in the respective temporal branch of the universe, which is viewable as a macroscopically continuous material system [16]. The irreversibility of either of the opposite time arrows and of any respective entropy growth thus result from such a generalization of the first law of thermodynamics as accounts for the gravitational energy-momentum balance as well.

References

[1] D. V. Sivukhin, General course of physics. Thermodynamics and molecular physics. Moscow, "Nauka" (1979) (in Russian).

[2] R. P. Feynman, R. B. Leighton, M. Sands, The Feynman Lectures on Physics. Vol. 1. Part 4. Kinetics • Heat • Sound. Translated by A. V. Efremova, G. I. Kopylova, Yu. A. Simonova, O. A. Khrustaleva, Edited by Ya. A. Smorodinsky, Publishing House "MIR", Moscow (1965) (in Russian).

[3] J. L. Lebowitz, Phys. Today **46**(9), 32–38 (1993);
J. L. Lebowitz, Physica A **194**, 1–27 (1993);
J. L. Lebowitz, Rev. Mod. Phys. **71**, S346–S357 (1999);
J. L. Lebowitz, Scholarpedia **3**(4), 3448 (2008);
see also the references in all these works.

[4] Part 1 in Ref. [5].

[5] R. Penrose, Cycles of Time. The Bodley Head, London (2010).

[6] A. Y. Klimenko, Phys. Scr. **94**, 034002 (2019);
A. Y. Klimenko, In: 2019-20 MATRIX Annals, Edited by D. R. Wood, J. de Gier, C. E. Praeger, T. Tao, pp. 387–409 (Springer 2021), arXiv:2001.00527 (2020);
see also the references in these works.

[7] R. Feynman, The Character of Physical Law. Translated by V. P. Golyshev, E. L. Nappelbaum (1968), Moscow, "Publishing House NTS ENAS" (2004) (in Russian), Lecture 5; See also Chapter 46 in Ref. [2].

[8] R. Peierls, Phys. Today **47**(11), 115–115 (1994).

[9] A. D. Sakharov, Sov. Phys. JETP **52**, 349–351 (1980).

[10] R. Penrose, Ann. N. Y. Acad. Sci. **571**, 249–264 (1989) and references therein;
see also §1.6 and §2.2 in Ref. [5].

[11] R. M. Wald, Studies in History and Philosophy of Modern Physics **37**, 394–398 (2006).

[12] E. B. Gliner, Sov. Phys. JETP **22**, 378–382 (1966).

[13] A. D. Sakharov, Sov. Phys. JETP **22**, 241–249 (1966).

[14] E. B. Gliner, Sov. Phys. Dokl. **15**, 559–561 (1970).

[15] N. Tsitverblit, https://doi.org/10.48550/arXiv.1306.5997 (2013);
also available at https://web.ma.utexas.edu/mp_arc-bin/mpa?yn=13-57.

[16] N. Tsitverblit, https://osf.io/preprints/inarxiv/t5u6v/ (2018);
also available at https://web.ma.utexas.edu/mp_arc-bin/mpa?yn=18-49.

[17] Apart from what is discussed in Ref. [16], the nature of cosmological redshift is commonly attributed to the effect of universe expansion. (See say Sec. 14.3 of Ref. [18], Sec. 1.2 of Ref. [19], Chapter 2 of Ref. [20], and Ref. [21].) This already implies that the traveling light characterizes the expanding medium as a whole, of which this light is a part. One could also note the typically observed transformation of a portion of the material energy for colliding dense objects (such as say black holes or neutron stars) into the energy of gravitational waves emitted with their collision (see say Ref. [59] in the present Ref. [16]). This could naturally be physically comprehended only when both the colliding objects and the gravitational waves are merely different phenomena within their overall material medium.

[18] S. Weinberg, Gravitation and Cosmology. John Wiley & Sons (1972).

[19] S. Weinberg, Cosmology. Oxford University Press, New York (2008).

[20] H. R. Quinn, Y. Nir, The Mystery of the Missing Antimatter. Princeton University Press, Princeton & Oxford (2008).

[21] C. H. Lineweaver, T. M. Davis, Sci. Am. **292**(3), 36–45 (2005).

[22] In terms of Ref. [16], expansion of the universe is a relative motion through flat background space-time. That gravitational waves propagate with the speed of light is in fact an indication of this flat space-time background as well. The theoretical achievability of an unlimited velocity of relative recession within the expanding cosmic medium is thus attributable to such a feature of general relativity as repulsion of the (decaying) vacuum phase. With no inertial density, such a part of the medium as the vacuum phase of matter could not define its own reference frame. This is what eventually renders the velocity of relative recession unlimited. Indeed, superluminal recession velocities are admittedly imputed to distinctions between the theories of general and special relativity [21, 23]. Except for such a unique phenomenon driven by the vacuum phase as the cosmological expansion, however, superluminal velocities are not typically expected in general relativity either.

[23] T. M. Davis, C. H. Lineweaver, Pub. Astron. Soc. Austr. **21**, 97–109 (2004).

[24] A. G. Riess *et al.* (The High-z Supernova Search Team Collaboration), Astron. J. **116**, 1009–1038 (1998);
S. Perlmutter *et al.* (The Supernova Cosmology Project Collaboration), Astrophys. J. **517**, 565–586 (1999);
D. H. Weinberg, M. J. Mortonson, D. J. Eisenstein, C. Hirata, A. G. Riess, E. Rozo, Phys. Rep. **530**, 87–255 (2013) and references therein;
D. Huterer and D. L. Shafer, Rep. Prog. Phys. **81**, 016901 (2018) and references therein.

[25] Instead of such a largely empiric description ignoring the existence of cosmological singularity as the ΛCDM model treated in Ref. [26], for example, it is the rigorous framework derived in Ref. [15] that ought to underlie any comparative analysis for the current rate of cosmological expansion. In particular, the squared Hubble parameter in its respective Friedmann equation [Eq. (2) hereinafter] for the ΛCDM model has to decrease with the dominant material density component to a constant value that has not yet been reached. In the framework of vacuum decay formalism of Ref. [15], however, the total energy density specifying the Hubble parameter [in Eq. (2) hereinafter] becomes nearly constant at such a late stage of cosmic evolution as the current one. This is suggested by the overall-energy conservation equation [Eq. (8) hereinafter] when the scale factor is relatively large enough to characterize this cosmological stage. Increasingly recognized recently [27], inadequacy of the ΛCDM model also ought to have other important consequences.

[26] G.-B. Zhao *et al.*, Nat. Astron. **1**, 627–632 (2017);
L. Verde, T. Treu, A. G. Riess, Nat. Astron. **3**, 891–895 (2019);
A. G. Riess, Nat. Rev. Phys. **2**, 10–12 (2020);
L. Knox, M. Millea, Phys. Rev. D **101**, 043533 (2020);
E. Di Valentino *et al.*, Class. Quant. Grav. **38**, 153001 (2021);
W. L. Freedman, Astrophys. J. **919**, 16 (2021);
see also the references in these works.

[27] M. S. Turner, Found. Phys. **48**, 1261–1278 (2018);
M. S. Turner, Annu. Rev. Nucl. Part. Sci. **72**, 1–35 (2022);
E. Abdalla *et al.*, J. High Energy Astrophys. **34**, 49–211 (2022);
L. Perivolaropoulos, F. Skara, New Astron. Rev. **95**, 101659 (2022);
P. J. E. Peebles, Ann. Phys. **447**, 169159 (2022).

[28] H. Alfvén, Rev. Mod. Phys. **37**, 652–665 (1965);
H. Alfvén, Phys. Today **24**(2), 28–33 (1971);
G. Steigman, Annu. Rev. Astron. Astrophys. **14**, 339–372 (1976);
F. Wilczek, Sci. Am. **243**(6), 82–91 (1980);
H. R. Quinn, Phys. Today **56**(2), 30–35 (2003);
M. Dine, A. Kusenko, Rev. Mod. Phys. **76**, 1–30 (2004);
G. Steigman, J. Cosmol. Astropart. Phys. 10 (2008) 001;
Ref. [20];
L. Canetti, M. Drewes, M. Shaposhnikov, New J. Phys. **14**, 095012 (2012);
L. Willmann, K. Jungmann, Annln. Phys. **528**, 108–114 (2016);
B. Garbrecht, Prog. Part. Nucl. Phys. **110**, 103727 (2020);
see also the references in all these works.

[29] L. Boyle, K. Finn, N. Turok, Phys. Rev. Lett. **121**, 251301 (1918);
S. J. Robles-Pérez, Universe **5**, 150 (2019);
S. J. Robles-Pérez, Acta Phys. Pol. B Proc. Suppl. **13**, 325–338 (2020).

[30] A. Friedmann, Z. Phys. **10**, 377–386 (1922) [Gen. Rel. Grav. **31**, 1991–2000 (1999)];
A. Friedmann, Z. Phys. **21**, 326–332 (1924) [Gen. Rel. Grav. **31**, 2001–2008 (1999)].

[31] Sec. 15.1 in Ref. [18], Sec. 1.5 in Ref. [19], and Sec. 3.1 in Ref. [32].

[32] E. W. Kolb, M. S. Turner, The Early Universe. CRC Press, Taylor & Francis Group (2018).

[33] In Sec. 2, the universe is conventionally treated as having a single time arrow. This treatment is seen below to apply to either of two temporal branches of the overall universe.

[34] In Refs. [18, 19, 32], Eq. (4) is treated as the second law of thermodynamics, whereas the adiabatic form of Eq. (4) (without an external heat supply) is referred to as the first law [32]. Such an interpretation of Eq. (4) has to imply that the existence of entropy is a consequence of the second law. According to Refs. [1, 2], however, Eq. (4) is also viewable as the first law for a quasi static process where the external heat supply is thus formulated in terms of entropy. This is why Eq. (4) is referred to as the first law herein as well.

[35] When thermodynamic parameters of the overall mixture of material and vacuum phases are treated here, the total number of particles in the mixture is viewed as constant. This number then includes both the particles of already created material phases and those that could potentially be created by decay of their vacuum phase of a nonzero energy density. It is the nonzero density of the vacuum phase that actually implies the existence of particles in their vacuum phase as well, although such particles are not physically countable until they arise as a material phase. When the first law of thermodynamics is used in a literature describing the thermodynamics of vacuum decay [36], the chemical-potential terms for the created material phases are also included because this law seems to be applied there to the real material phases alone. When the fundamental nature of thermodynamic irreversibility is examined herein for such a closed material system as the universe [33], however, one has to treat the thermodynamics of all phases for what comprises the material energy-momentum tensor. These thus also inevitably include the decaying vacuum phase.

[36] J. Solà Peracaula, H. Yu, Gen. Rel. Grav. **52**, 17 (2020) and references therein.

[37] J. A. S. Lima, S. Basilakos, J. Solà, Mon. Not. Roy. Astron. Soc. **431**, 923–929 (2013).

[38] In the framework of Friedmann evolution of the universe, the concept of thermodynamic equilibrium for the universe as a whole reduces to that for its comoving volume alone.

[39] As discussed in Secs. 3.1 and 3.2 (and references therein), a material phase has to first emerge at a finitely small $a > 0$. Its emergence is also viewed there as the onset of time.

[40] Sec. 3.4 in Ref. [32].

[41] Along with Eqs. (5) and (8), Eq. (10) could of course be also used, instead of Eq. (7), for a simple derivation of Eq. (9).

[42] The only irreversible process that could potentially be viewed as capable of defining the thermodynamic time arrow in the framework of Friedmann expansion is bulk dissipation [43]. Its effect is then reduced to changing the pressure in Eqs. (1) and (8) by a term proportional to $\dot{a}/a$. When ρ and p are viewed as the functions of a in Eqs. (1) and (2) [15], however, the time-reversal symmetry of these equations applies both to such a resulting overall effective pressure and to the pressure when the bulk dissipation term is ignored. It thus suggests that this term has to vanish throughout the Friedmann expansion.

[43] S. Weinberg, Astrophys. J **168**, 175–194 (1971);
see also Secs. 15.10 and 15.11 in Ref. [18].

[44] Even when a perturbation of Friedmann equilibria could not grow, it generally introduces dissipative effects [43] that are absent in the Friedmann formulation itself [42]. In particular, such perturbed Friedmann equations are discussed in Sec. 15.10 of Ref. [18]. Dissipative processes triggered in the perturbed Friedmann equilibria thus increase the universe entropy [43] irrespective of whether these equilibria are gravitationally unstable.

[45] J. H. Jeans, Phil. Trans. R. Soc. A **199**, 1–53 (1902);
E. Lifshitz, J. Phys. (USSR) **10**, 116–129 (1946) [Gen. Rel. Grav. **49**, 18 (2017)];
G. Gamow, Phys. Rev. **74**, 505–506 (1948);
W. B. Bonnor, Mon. Not. R. Astron. Soc. **117**, 104–117 (1957);
E. M. Lifshitz, I. M. Khalatnikov, Sov. Phys. Usp. **6**, 495–522 (1964);
D. Layzer, Annu. Rev. Astron. Astrophys. **2**, 341–362 (1964);
P. J. E. Peebles, Astrophys. J. **142**, 1317–1326 (1965);
Secs. 15.9 and 15.10 in Ref. [18];
B. J. T. Jones, Rev. Mod. Phys. **48**, 107–149 (1976);
Ya. B. Zel'dovich, Annu. Rev. Fluid Mech. **9**, 215–228 (1977);
S. F. Shandarin, A. G. Doroshkevich, Ya. B. Zel'dovich, Sov. Phys. Usp. **26**, 46–76 (1983);
S. F. Shandarin, Ya. B. Zeldovich, Rev. Mod. Phys. **61**, 185–220 (1989);
Chapters 5–8 and Appendix F in Ref. [19];
see also the references in all these works.

[46] In particular, extension of the entropy concept to such a complex state of multiple local equilibria is discussed in §42 of Ref. [1].

[47] Ya. B. Zel'dovich, Sov. Phys. JETP **37**, 33–37 (1973).

[48] J. D. Bekenstein, Phys. Rev. D **7**, 2333–2346 (1973);
S. W. Hawking, Comm. Math. Phys. **43**, 199–220 (1975);
T. Jacobson, Phys. Rev. Lett. **75**, 1260–1263 (1995);
R. M. Wald, Liv. Rev. Rel. **4**, 6 (2001);
E. Verlinde, J. High Energy Phys. 04 (2011) 029;
T. Padmanabhan, Curr. Sci. **109**, 2236–2242 (2015);
see also the references in these works.

[49] V. B. Berestetskií, E. M. Lifshitz, L. P. Pitaevskií, Quantum Electrodynamics, Moscow, "Fizmatlit" (2002) (in Russian).

[50] Although time is viewable as a monotonically increasing measure of a certain irreversible physical process, the Lorentz and CPT invariances suggest that this process has to be of such a universally applicable nature as endows time with the same status as possessed by the spatial coordinates. Unlike a spatial coordinate, however, time is thus also irreversible. Except for the joint initial moment, in particular, two opposite time arrows are outside the light cones of each other. Even when events belonging to such arrows have the same spatial location, therefore, they are still mutually inaccessible for all their respectively defined interactions merely because of the irreversibility of either time arrow.

[51] The notion of PT signature refers herein to the respective signs of material phases created or absorbed by the vacuum phase per such equations as Eqs. (12) and (13).

[52] In terms of Ref. [16], the medium with one PT signature [51] thus forms its space-time curvature independently of that with the opposite signature. Due to their opposite time arrows, these two media and space-time curvatures are inaccessible to each other [50].

[53] Eqs. (12) and (13) apply to the flat space-time, which is what the empty background in general relativity is [16]. Space-time curvature is a characteristic of either created material phase and its vacuum-phase progenitor [16, 52]. The opposite time arrows are still independently embodied by the respective effects of attractive gravitation for the two created material phases, by which the vacuum phase is not affected. Due to the CPT symmetry, such effects on the overall space-time curvature are thus mutually canceled at the creation or annihilation of these coupled phases, which are the events shared by both their time arrows in the same space. Since the vacuum phase is also symmetric to CPT, it separately opposes attractive gravitation for either of the material phases arising from its decay in the framework of the energy-momentum balance for the respective time arrow. These identical and opposite repulsive effects of the vacuum phase on the overall space-time curvature when the material phases are created or annihilated hence likewise cancel each other. Invariant to CPT, the space-time where real particle pairs are created or absorbed by their vacuum phase is thus flat. For either such a particle of the pair, its phase is then still described by the separate Einstein field equations. These independently define the arrow of time for such a material phase in terms of what underlies the respective deviation from the initial Friedmann solution corresponding to this time arrow.

[54] A measure of the overall material phase created cosmologically with the same arrow of time from decay of its vacuum phase is viewed in a literature on vacuum decay [36] as mimicking an entropy growth by itself. Such a thermodynamic time arrow is thus independent of the entropy produced by dissipative processes and gravitational instability for the created material phase. The analysis in Ref. [36] still seems to apply to the overall material phase alone [35], due to which the treated thermodynamic system with its chemical-potential terms is not a closed one. As likewise emphasized in Ref. [35], however, the vacuum phase decaying into this material phase is also a part of the material energy-momentum. It thus ought to be accounted for when the irreversible thermodynamics of such a closed material system as either temporal branch of the universe is considered. The overall number of particles in this system is then viewable as constant [35]. The thermodynamic nature of time arrow is therefore reduced only to the entropy growth produced by such nonequilibrium effects driven by attractive gravitation for the overall material phase with the same time arrow as dissipation [44] and gravitational instability [45].

[55] According to the nature of decay of the vacuum phase discussed in Sec. 3.3, physically distinct matter and antimatter produced by the decay process have to consistently arise with such opposite time arrows as either of them is largely the same. They are thus natural parts of the respective overall material phases with opposite time arrows created out of their vacuum phase. Even without the discussion in Sec. 3.3, however, one could merely view the phases arising from vacuum decay as having opposite time arrows, by which they are also separated. This applies then irrespective of whether such a macroscopic separation is actually between the physically distinct matter and antimatter as well.

[56] In view of Eq. (3), Eqs. (1) and (2) imply that the time interval separating $a = 0$ from a sufficiently large a may look infinite. The times defined by Eqs. (14) with $a_i = 0$ as physically meaningful characteristics of a comoving Friedmann volume could still have only finite values. However, such times have no physical meaning at $a = 0$. Their onset could then only be at a finite $a = a_i > 0$, when the temperature and density of either material phase first arising from vacuum decay are also finitely small. The times in Eqs. (14) are thus finite.

[57] The homogeneous-universe version of Eqs. (14),

$$t_{\pm} = \alpha_{\pm} \int_{a_i}^{a} [\rho_{\pm}(x) + 3p_{\pm}(x)] 3x^2 dx, \tag{H14}$$

is alone unsuitable for generally defining $t_{\pm}$. Indeed, the comoving volume typically turns inhomogeneous due to either transient gravitational perturbations themselves or their growth resulting from gravitational instability.

[58] Local processes are still known to be irreversible even when they are neither directly driven by the effects of attractive gravitation nor expected to be sensitive to such effects from the material phase newly created cosmologically with their time arrow. However, the microscopic constituents of these processes carry such a quantum property as their single arrow of time manifested in terms of the principal ability to gravitationally attract and be attracted by other carriers of the same time arrow. Even when gravitational attraction does not underlie the dynamics of these microscopic constituents, therefore, the irreversibility of such a dynamics is encoded in their material phase as the single available time arrow defined by the cosmic creation of this phase. Being the most likely, their largest-entropy state is thus reached with only one time arrow [8].

[59] W. Heisenberg, Z. Phys. **43**, 172–198 (1927);
N. Bohr, Nature Suppl. April 14, 580–590 (1928);
H. P. Robertson, Phys. Rev. **34**, 163–164 (1929);
L. Mandelstam, I. Tamm, J. Phys. (USSR) **9**, 249–254 (1945);
E. P. Wigner, In: Aspects of Quantum Theory, Edited by A. Salam, E. P. Wigner, pp. 237–247 (Cambridge University Press 1972);
J. Hilgevoord, Am. J. Phys. **64**, 1451–1456 (1996);
P. Busch, In: Time in Quantum Mechanics, Edited by J. G. Muga, R. Sala Mayato, Í. L. Egusquiza, pp. 73–105, Lect. Notes Phys. **734** (Springer, Berlin Heidelberg 2008) and references therein.

[60] As discussed say by Hilgevoord (1996) in Ref. [59], an appropriate operator commutation relation generally implies the uncertainty relation for the respective variables only when both these variables are characteristics of the quantum system in question. One could not say so about such an external parameter as time when microscopic phenomena, whose variables arise in their operator commutation relation, are formally isolated from the macroscopic phenomena by which the time is defined. When treated as a quantum system, however, either temporal branch of the overall universe homogeneously created from the vacuum phase is characterized both by the time defined in one of Eqs. (14) and by an appropriate energy portion for the interval of such a time in the uncertainty relation.

[61] The first mean value theorem for definite integrals is used in Eq. (15).

[62] In the absence of real material phases for $a < a_i$ [56], $a \in (0, a_i)$ in Eq. (15) is still identifiable by such respective virtual phases as result in their real emergence at $a = a_i$ when described by Eqs. (1) and (2). The rest of the vacuum phase thus drives their virtual cosmic expansion. The opposite time arrows in such Eqs. (1) and (2) are then still thermodynamically definable by the independent effects of attractive gravitation for their virtual phases [44].

[63] As suggested in Ref. [62], the virtual time arrows are only of a thermodynamic nature. Consistency of the uncertainty time intervals (defined by the respective virtual gravitational energies) with Eqs. (14) for $a_i = 0$ does not then imply the existence of virtual cosmological time arrows. This is thus found to be in contrast to such real arrows arising from decay of the vacuum phase.

[64] As discussed for the present framework in Ref. [16], the singularity of a Schwarzschild black hole is eliminated when the collapsing material phases turn into their vacuum phase. Generally hypothesized in Ref. [12], this has also been specifically suggested by models considered in Ref. [65]. Since the spatial location of such a black hole stands for either temporal branch of the universe, the material phases with both opposite time arrows arise within their respective horizons. As suggested herein, this is so even when the opposite PT signatures comprise the only distinction between the material phases before their transition to the vacuum phase. Analogously to the universe at $a \to 0$, the joint phase transition of the (mutually inaccessible) material phases with opposite time arrows thus enhances the residual vacuum phase around their black hole centers. (These centers are shared by the vacuum phase [66], where attractive gravitation from their material phases has no horizons and the real time arrows vanish.) Quantum mechanically, such a transition would be described with annihilation operators as in Eq. (13) [53].

[65] I. Dymnikova, Gen. Rel. Grav. **24**, 235–242 (1992);
P. O. Mazur, E. Mottola, Proc. Nat. Acad. Sci. USA **101**, 9545–9550 (2004);
M. Visser, D. L. Wiltshire, Class. Quant. Grav. **21**, 1135–1151 (2004);
S. Ansoldi, arXiv:0802.0330 (2008) and references therein;
P. O. Mazur, E. Mottola, Universe **9**, 88 (2023) and references therein.

[66] D. Farrah *et al.*, Astrophys. J. Lett. **944**, L31 (2023).

[67] When the PT signatures of matter and antimatter are identical, per the CPT symmetry, the P symmetry of either minor of these phases is opposite to that of its dominant phase.

[68] T. D. Lee, C. N. Yang, Phys. Rev. **104**, 254–258 (1956);
T. D. Lee, R. Oehme, C. N. Yang, Phys. Rev. **106**, 340–345 (1957);
B. L. Ioffe, L. B. Okun', A. P. Rudik, Sov. Phys. JETP **5**, 328–330 (1957);
C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, R. P. Hudson, Phys. Rev. **105**, 1413–1415 (1957);
R. L. Garwin, L. M. Lederman, M. Weinrich, Phys. Rev. **105**, 1415–1417 (1957);
A. Roy, Resonance **10**, 164–175 (2005);
C.-S. Wu, In: Nishina Memorial Lectures, Edited by Nishina Memorial Foundation, pp. 43–70, Lect. Notes Phys. **746** (Springer, Tokyo 2008) and references therein;
Chapter 7 in Ref. [20].

[69] N. Cabibbo, Phys. Rev. Lett. **10**, 531–533 (1963);
J. H. Christenson, J. W. Cronin, V. L. Fitch, R. Turlay, Phys. Rev. Lett. **13**, 138–140 (1964);
M. Kobayashi, T. Maskawa, Prog. Theor. Phys. **49**, 652–657 (1973);
A. Alavi-Harati *et al.* (KTeV Collaboration), Phys. Rev. Lett. **83**, 22–27 (1999);
V. Fanti *et al.* (NA48 Collaboration), Phys. Lett. B **465**, 335–348 (1999);
B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. Lett. **87**, 091801 (2001);
K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **87**, 091802 (2001);
Chapters 8, 14, 15, and 17 in Ref. [20];
R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett **110**, 221601 (2013);
R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **122**, 211803 (2019);
R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **124**, 031801 (2020);
see also the references in all these works.

[70] Weak interactions involve only the left chirality components of their fields. [Defined in terms of the γ^5 Dirac matrix [49], such components are selected with $(\mathbf{I} - \gamma^5)/2$.] When particles were created as massless from the vacuum phase at a very high temperature, however, their chirality was univocally identified by the respective helicity. Given that these massless particles had the time arrow of our temporal branch of the universe, the spatial part of their PT signature is then what ought to render their helicity left-handed alone. Such massless antiparticles arising for our time arrow accordingly had to have only the right-handed helicity, which corresponds both to their chirality and to the CPT symmetry [67]. The observed chirality of massive weakly interacting particles and antiparticles could thus be due to the spatial part of the PT signature for our temporal branch of the universe underlying the original selection of parity-breaking helicities for their respective massless progenitors. Participating in weak interactions alone, neutrinos (and antineutrinos) happen to largely convey this signature due to their nearly negligible mass.

In the weak interactions for massive fields with our time arrow, P violation is thus attributable to such helicities of these particles and antiparticles in the experimental reference frame as conserve the overall spin angular momentum under the left chirality of these interactions (as the total momentum is also conserved) [68]. This chirality constraint is effective due to the very small neutrino mass. Since time arises twice in the definition of helicity, however, CP still remains conserved then, although C is also separately violated. CP violation in such weak interactions is thus permitted only when the same arrow of time is rendered distinguishable in the behaviour of particles and antiparticles [69].

[71] Chapters 19 and 20 in Ref. [20];
K. Abe *et al.* (The T2K Collaboration), Nature **580**, 339–344 (2020) and references therein;
P. B. Denton, J. Gehrlein, R. Pestes, Phys. Rev. Lett. **126**, 051801 (2021).

[72] This putative equilibrium could say be of a global nature when engendered by dissipative processes alone and its relevant background Friedmann equilibria are gravitationally stable [44]. Otherwise, it could be a complex global state of multiple local equilibria arising from the gravitational instability of such background Friedmann equilibria, as discussed in Sec. 3.1.

[73] The consequence of Eq. (18) in the nearby square brackets follows when Clairaut's theorem is applied by induction to $\tilde{S}(t_-, t_+)$ and its partial derivatives of all orders.

[74] The opposite time arrows for portions of their respective material phases could still also merge in the future when these portions form black holes. In the black hole centers, the material phases with opposite arrows of time undergo a joint transition to their vacuum phase, where their real time arrows vanish and black hole horizons turn irrelevant [64, 66].

[75] As discussed in §44 of Ref. [1], T. A. Afanasyeva-Ehrenfest originally suggested to reduce the second law of thermodynamics just to the existence of entropy as a function of state.